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Direct Reduction: A Review of Commercial Processes

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Direct Reduction: A Review of Commercial Processes

by

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ABSTRACT

Direct reduction commercial processes for ironmaking have been reviewed. The potential for environmental degradation appears to be minimal. A detailed environmental assessment does not appear to be warranted. It is recommended that samples of scrubber water and sludge material be collected and characterized from several gas reductant reactor systems. It is also recommended that rotary kiln solid reductant reactors be sampled to ensure that the final gas effluent does not contain harmful concentrations of organic species, sulfur oxides and trace metal contaminants; and that such systems be monitored for harmful rates of fugitive emissions.

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SECTION 1

INTRODUCTION

Definition

For the purpose of this report "direct reduction" is defined as the reduction of iron oxides by the use of either solid or gaseous reductants to produce a solid iron product.

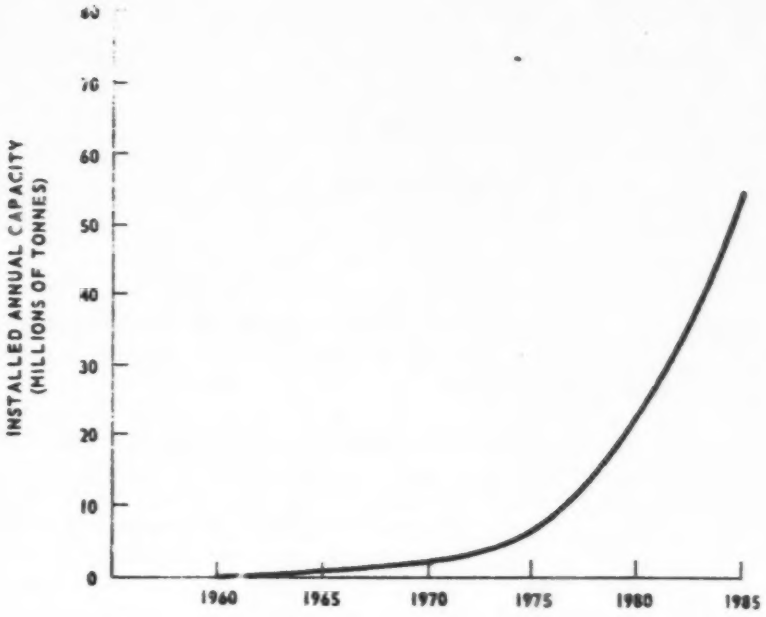
It would be more appropriate to designate the "direct reduction" processes as alternative processes, i.e., alternatives to the production of iron in the conventional blast furnace. The reactions that occur in the "direct reduction" processes are no more "direct" in producing iron than those reactions occurring in the blast furnace. The difference between the process types is that the direct reduction processes operate at much lower temperatures than does the blast furnace and therefore produce a solid iron product instead of a liquid product.

Statistics of Growth

Present day large scale commercialization of the direct reduction processes dates back only about 25 years (however, the first iron produced was probably via direct reduction processes practiced over 3000 years ago). Growth and projects of growth are given in two graphs (1-3) presented in Figure 1. The most recent projections (2,4,5) suggest that production may achieve about 50 million tonnes of direct reduced product by 1985 with the possibility that the production could reach 100 million tonnes (3,5). This could mean that about 5-10 percent of the world's iron may be produced by direct reduction processes in 1985. In 1978 about 3 percent of the world's iron was produced by direct reduction processes.

Miller (4) has tabulated the regional distribution of direct reduction plants by production and by number of plant installations (Table 1). In 1978 almost three-fourths of the world's sponge iron was produced by the developing world: Latin America (30.9%), Middle East (19.7%), Africa (8.4%), and Asia (13.9%); about one-sixth was produced in North America. The projected production distribution in 1985 is about two-thirds for the developing world, one-eighth for North America. The number of direct reduction plants in the world at the end of 1978 was 55. This number is anticipated to double by 1985 (4).

Miller (4) has also tabulated the individual plants presently operating, those scheduled for completion by 1980, and those planned for operation by



Greenwalt, R. and J. Stephensen (2)
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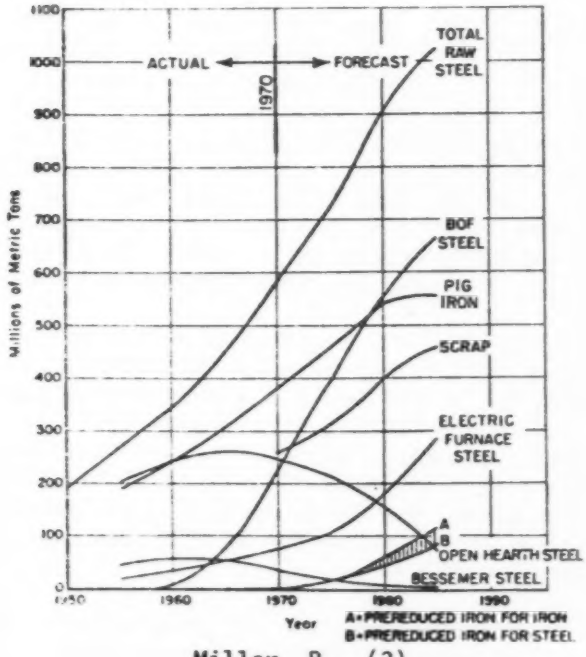

Miller, R. (3)

Figure 1. Growth in production of direct reduction sponge iron.

TABLE 1. REGIONAL DISTRIBUTION OF DIRECT REDUCTION PLANTS (4)

Distribution by Production

Region	Production: 1978 kt/year	1978 % world total	1979 kt/year	1979 % world total	1980 kt/year	1980 % world total	1981-85 kt/year	1981-85 % world total
North America	2935	16.9	2935	11.3	2935	9.2	6455	12.7
Latin America	5345	30.9	8645	33.4	9065	28.5	15035	29.5
Western Europe	1650	9.5	1650	6.4	3650	11.5	5700	11.2
Eastern Europe			2500	9.7	5000	15.7	5000	9.8
Middle East	3415	19.7	4415	17.1	5215	18.4	7915	15.6
Africa	1450	8.4	1450	5.6	1700	5.3	5100	10.0
Asia	2409	13.9	4134	16.0	4134	13.0	4194	8.2
Oceania	120	0.7	120	0.4	120	0.4	1520	3.0
Total	17324	100	25849	100	31819	100	50920	100

Distribution by Number of Installations

Region	Installations: 1978 No.	1978 % of total	1979 No.	1979 % of total	1980 No.	1980 % of total	1981-85 No.	1981-85 % of total
North America	11	19.6	11	18.1	11	16.7	16	15.8
Latin America	16	28.6	18	29.5	19	28.8	33	32.7
Western Europe	9	16.1	9	14.8	11	16.7	15	14.8
Eastern Europe	0		1	1.6	2	3.0	2	2.0
Middle East	4	7.1	5	8.2	6	7.6	9	8.9
Africa	3	5.4	3	4.9	4	6.0	9	8.9
Asia	12	21.4	13	21.3	13	19.7	14	13.9
Oceania	1	1.8	1	1.6	1	1.5	3	3.0
Total	56	100	61	100	67	100	101	100

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1985. His results are presented as Table 2. (It is known (6) that the Steel Company of Canada has not started up their facility after shutting down in late 1976. Also Hecla Mining has closed down its mining operation in Casa Grande, Arizona.) Note that the United States' direct reduction capacity is indeed small; e.g., 11.2% of the world's capacity in 1977.

Reasons for Growth

The reasons for the optimism in projected growth of direct reduction produced iron are:

1. A high purity product can be produced. The conversion of iron oxide to iron is accomplished in the solid state; i.e., a liquid iron product is not produced as in the blast furnace. This is because the reaction temperatures are much lower in direct reduction furnaces. Less reduction of gangue material occurs and the solubility of solid iron for impurities is much less in the solid state than in the liquid state. Secondly the product is relatively pure iron because the feed materials are chosen to have low impurity levels, especially sulfur and phosphorus.

2. A wide variety of reducing agents are candidates for use in the direct reduction process; e.g., coal, coke, charcoal, reformed natural gas, products of coal gasification, oil, coke oven gas, and coke breeze. The blast furnace requires coke as the primary reductant.

3. Refractory life is longer and less expensive refractories are required for the direct reduction furnaces than are required in the blast furnace because of the lower furnace operating temperatures.

4. Developing nations can enter the steel business on a moderate scale with a smaller investment in a direct reduction-electric arc steelmaking furnace (DR-EAF) combination as compared to the coke, blast furnace, basic oxygen furnace combination; i.e., the capital cost is only about 60 percent of the conventional process capital cost (7-9).

5. Some developing nations have rich iron ore deposits and natural gas or oil supplies but do not have metallurgical grade coals available.

6. Developing nations need to develop their basic industries and therefore prefer to pretreat their ores before shipping to other nations, i.e.; keep as much industry home as possible.

7. Direct reduction products can be used as feedstock for supplementing scrap in an electric furnace, as a coolant feed material for the basic oxygen furnace operations, and as an iron value added to increase the productivity of a blast furnace (4).

TABLE 2. ANNUAL CAPACITY OF DIRECT REDUCTION PLANTS, 1977, 1980, 1985 (4)
Plants in Operation on 1 January 1977*

Plant No.	Year of Start	Company	Country	Process	Reductant	Annual rated capacity of DRI, kt
1-2	1954	Hoganas Grangesberg	Sweden	Hoganas	Coke breeze	170
3	1954	Hoganas Corporation	USA	Hoganas	Coke breeze	70
4-6	1954	SKF etc.	Sweden	Wiberg	Coke breeze	90
7	1957	Tohoku-Satetsu	Japan	Rotary kiln	Coal	24
8	1957	HYLSA-Monterrey I	Mexico	HyL	Natural gas	100
9	1960	HYLSA-Monterrey II	Mexico	HyL	Natural gas	270
10	1964	Hitachi Metals	Japan	Wiberg	Coke breeze	10
11	1967	TAMSA	Mexico	HyL	Natural gas	280
12	1968	Anglo-American Corp.	South Africa	Highveld kiln	Coal	1000
13	1969	HYLSA-Puebla I	Mexico	HyL	Natural gas	315
14	1969	Oregon Steel Mills	USA	Midrex	Natural gas	300
15	1969	Kawasaki Steel Co.	Japan	Kawasaki	Coke breeze	72
16	1970	New Zealand Steel	New Zealand	SL-RN	Coal	120
17	1970	Thyssen-Purofer	West Germany	Purofer	Natural gas/CO gas	150
18	1971	Georgetown Steel Co.	USA	Midrex	Natural gas	400
19	1971	Nippon Steel Co.	Japan	Koho	Coke breeze	48
20	1972	Kawasaki Steel Co.	Japan	Kawasaki	Coke breeze	240
21	1972	Hamburger Stahlwerke	West Germany	Midrex	Natural gas	400
22	1972	Armco Steel Corp.	USA	Armco	Natural gas	330
23	1973	Acos Finos Piratini	Brazil	SL-RN	Coal	60
24	1973	Dunswart Iron & Steel	South Africa	Krupp	Coal	150
25	1973	SIDBEC-DOSCO	Canada	Midrex	Natural gas	400
26	1973	MINORCA	Venezuela	HIB	Natural gas	650
27	1974	USIBA	Brazil	HyL	Natural gas	250
28	1974	HYLSA-Monterey III	Mexico	HyL	Natural gas	475
29	1974	Nippon Kokan KK	Japan	SL-RN	Coal	350
30	1975	Steel Co. of Canada	Canada	SL-RN	Coal	360
31	1975	Hecla Mining Co.	USA	SL-RN	Coal	60
32	1975	Sumitomo Metals Co.	Japan	Sumitomo	Coal	240
33	1975	Sumitomo Metals Co.	Japan	Kabota	Coal	210
34	1975	Allis Chalmers Co.	Canada	ACCAR	Coal,oil,gas	50
35	1976	Dalmine-Siderca	Argentina	Midrex	Natural gas	330
36	1976	Sudbury Metals Co.	Canada	ACCAR	Natural gas,oil	240
37	1976	Fior de Venez,S.A.	Venezuela	FIOR	Natural gas	400

(cont'd)

Table 2 (Continued)*

38	1976	Nippon Steel Co.	Japan	NSC	Oil	150
39	1976	Ferriere di Arvedi	Italy	Kinglor-Metor	Coal	40
Total						8804

Plants Under Contract at Start of 1977 and Scheduled for Completion by 1980

Plant No.	Year of Start	Company	Country	Process	Reductant	Annual rated capacity of DRI, kt
40	1977	SIDBEC-DOSCO II	Canada	Midrex	Natural gas	625
41	1977	SIDOR III	Venezuela	Midrex	Natural gas	360
42	1977	DIDOR III	Venezuela	HyL	Natural gas	360
43	1977	COSIGUA	Brazil	Purofer	Gasified oil	350
44	1977	NISIC	Iran	Purofer	Natural gas	330
45	1977	HYLSA-Puebla II	Mexico	HyL	Natural gas	625
46	1977	Iraq Iron & Steel Co.	Iraq	HyL	Natural gas	1485
47	1977	Anglo-American Corp.	South Africa	Highveld kiln	Coal	300
48	1977	Consolidated Gold Fields	USA	Hockin kiln	Coal	100
49	1977	Kawasaki Steel Co.	Japan	Kawasaki	Coke breeze	250
50	1977	Nippon Steel Co.	Japan	NSC	Oil	240
51	1978	NISIC	Iran	Midrex	Natural gas	1200
52	1978	SIDERPERU	Peru	SL-RN	Coal	100
53	1978	Acindar	Argentina	Midrex	Natural gas	420
54	1978	BSC-Hunterston	UK	Midrex	Natural gas	800
55	1978	Qatar Steel Co.	Qatar	Midrex	Natural gas	400
56	1978	PT Krakatau	Indonesia	HyL	Natural gas	575
57	1979	NISIC	Iran	HyL	Natural gas	1000
58	1979	PT Krakatau	Indonesia	HyL	Natural gas	1725
59	1979	SIDOR IV	Venezuela	Midrex	Natural gas	1200
60	1979	SIDOR IV	Venezuela	HyL	Natural gas	2100
61	1979	USSR-Kurak	USSR	Midrex	Natural gas	2500
62	1980	North Sea Iron Co.	UK	Purofer	Natural gas	800
63	1980	Nord. Ferrowerke	West Germany	Midrex	Natural gas	1200
64	1980	USSR-Kurak	USSR	Midrex	Natural gas	2500
65	1980	ISCOTT	Trinidad-Tobago	Midrex	Natural gas	420
66	1980	TIKA	Zambia	HyL	Gasified naphtha	250
67	1980	Saudi Arabia-Jubail	Saudi Arabia	Midrex	Natural gas	800
Total						23015

TABLE 2 (Continued).*

Annual Capacity of Direct Reduction Plants 1977, 1980, 1985 (4).
Projects Planned for Operation Between 1981 and 1985

Plant No.	Country	Company and location	Probable Reductant	Annual rated capacity of DRI, kt
68	USA	Texas Ferroreduction	Natural gas	900
69	USA	Gulf Coast Consortium	Natural gas	1500
70	Canada	Interprovincial Iron Co.	Coal	400
71	Argentina	Gurmendi	Natural gas	400
72	Bolivia	SIDERSA (Santa Cruz)	Natural gas	200
73	Brazil	COSIGUA II	Gasified oil	350
74	Brazil	COFAVI	Gasified oil	350
75	Brazil	USIBA II	Natural gas	300
76	Brazil	IMBITUBA(Sta.Catarina)	Gasified coal	400
77	Brazil	Piritim II	Coal	200
78	Mexico	TAMSA II	Natural gas	300
79	Venezuela	FIOR de Venezuela	Natural gas	2000
80	Italy	Adriatic Consortium	Natural gas	800
81	Spain	Sid. Gibraltar	Liquified natural gas	450
82	Spain	PREPELSA (Huelva)	Liquified natural gas	500
83	Algeria	SNS (Jijel)	Natural gas	1200
84	Egypt	Government (Helwan)	Natural gas	400
85	Tunisia	Government (Gabes)	Natural gas	800
86	Turkey	EDAS		400
87	Iran	NISIC (Bandar Abbas)	Natural gas	2800
88	Iran	NISIC (Esfahan)	Natural gas	1200
89	South Africa	SCAW & Anglo-American	Coal	200
90	New Zealand	New Zealand II	Coal	200
91	USA	Republic Steel (Massillon)	Coal	360
92	USA	Republic Steel (Gadsden)	Coal	360
93	El Salvador	Government (Acujutla)	Coal	160
94	Argentina	HIPASAM (Punto Colorado)	Natural gas	400
95	Argentina	Lucini	Natural gas	400
96	Brazil	DEDINI	Coal	400
97	Brazil	IKOSA-Pains	By-product gas	160
98	Brazil	Mendez Junior	By-product gas	350
99	Brazil	Mannesmann	By-product gas	400
100	Colombia	ACENOR (Barranquilla)	Natural gas	200
101	Ecuador	ECUASIDOR		400
102	Greece	SIDERHELLAS	Natural gas	300
103	Abu Dhabi	Government	Natural gas	400
104	Libya	Government (Misurata)	Natural gas	500
105	Morocco	Government	Natural gas	300
106	India	Government(AndraPradesh)	Coal	60
107	Australia	Hamersley Iron Co.	Natural gas	1200
Total				22600

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8. There will be a deficit in scrap availability by 1980 (10). Direct reduction sponge iron is viewed as a good substitute feed material.

9. The time required for commissioning a DR/EAF steel plant is about 2 to 3 years compared with 5 to 7 years for a conventional integrated steel plant (9).

10. Air pollution problems are minimized in a gas direct reduction plant because all gases are cleaned and recycled. One of the main air pollution producing stages in the conventional blast furnace is cokemaking which is not required in a gas D.R. facility (9).

11. Transferability of technology has been demonstrated by fast start-ups of new plants. This represents an important economic advantage (4).

12. Energy requirements are less for the DR-EAF process than for the conventional coke-blast furnace-BOF process (9).

13. Production facilities have been constructed to produce over a million metric tons per year of D.R. iron; i.e., two D.R. furnaces are presently used to accomplish this. It is anticipated that single furnaces with capacities of a million tons per year will be possible in the near future (9).

Terms and Nomenclature

Many articles have been published on direct reduction processes. The nomenclature used by the various authors is sometimes confusing and contradictory. Therefore, some of the terms and their various meanings will be presented in this section.

The charge fed to the reduction reactor is an iron oxide containing material. It may be ore lumps, ore fines, pelletized agglomerates, formed briquettes, or a combination of several of these materials. In the literature, the feed material may be simply characterized as ore, lump ore, nature ore, mineral ore, lump oxide, pellets, pelletized ore, pelletized oxide, or pelletized fines.

The product of the direct reduction reaction is a reduced material that contains metallic iron, some form of iron oxide, some iron carbide, and gangue that was contained in the original feed. This product is called sponge iron, luppen, metallized iron, metallized product, reduced iron, direct reduced iron, or a trade name, such as Midrex iron or HyL iron.

The reducing reactions remove oxygen from the iron oxides. A measure of the success of accomplishing this is described in several ways.

Percent metallization or degree of metallization or metallization is defined as

$$\% \text{ Met.} = \frac{\% \text{ Fe (as metal)}}{\% \text{ Fe (total)}} \times 100$$

It is the percent of iron present in the feed material that has been converted to metallic iron.

Equivalent metallization is defined as

$$\% \text{ Eq. Met.} = \% \text{ Met.} + 6 \text{ (\%C in sponge)}.$$

This term is used in presentations on the HyL process but has not been widely accepted.

Degree or Percent of Reduction is defined as:

$$\% \text{ Reduction} = \frac{\text{Oxygen removal from feed}}{\text{Original oxygen combined with iron}}$$

The terms percent reduction and percent metallization are not the same, and percent metallization or simply metallization is the normally reported value; i.e., metallization is more descriptive of how effective the reduction was in producing metallic iron.

It is also important to know how much metallic iron is present in the final product; i.e., the weight of metallic iron divided by the weight of product.

$$\% \text{ Fe} = \frac{\text{Wt}_{(\text{Fe})}}{\text{Wt}_{(\text{product})}} \times 100$$

The metallization and the metallic iron percentages are normally not the same numerical value; e.g., for a feedstock that contains 65 percent iron that is reduced to give a 90 percent metallization, the metallic iron content is about 86 percent. Bertram (11) points out that the two terms, metallization and metallic iron, have sometimes been used interchangeably and, therefore, care should be taken to understand how the author has performed his calculations.

SECTION 2

DIRECT REDUCTION PROCESSES

Introduction

More than 1200 patents have been issued covering various aspects of proposed direct reduction processes. Nearly 100 direct reduction schemes were examined by iron and steel producers between 1950 and 1975 (7). Of the many proposed and piloted processes only 12 major designs have progressed to commercial application. At the end of 1978 there were 55 direct reduction plants in the world (1). Thirty-seven of these plants use a gas reductant. Twenty-five of the 37 plants are based on either the HyL or Midrex process. Eighteen of the 55 plants use a solid reductant. Fourteen of the solid reductant systems are rotary kiln operations and use coal or coke breeze as the reductant.

Kalla and Steffen (1) present an interesting display of the distribution of process types used in sponge iron production (July 1977). See Figure 2. Note that most of the world's sponge iron is produced by gas reduction processes.

As already noted, there are two broad classes of direct reduction processes; i.e., gas reductant systems and solid reduction systems. A further sub-division is normally made in the literature according to the type of furnace; i.e., shaft, rotary kiln, or fluidized bed. Individual direct reduction systems will be described in the following section.

Systems

A summary of sponge iron production capacity by the type of process is presented in Table 3.

The gas reductant systems that use a shaft vessel as the reactor are the Midrex (Korf Industries), Purofer (Thyssen), Armco (Armco Steel), and Wiberg processes. These are all moving bed reactors; i.e., the solid feedstock moves in a direction countercurrent to the flow of reducing gas. The processes differ mainly in the way the reducing gas is produced and circulated and the shape of the shaft. Also a major difference in the Purofer process is that the product is discharged hot into a briquetting system whereas all the other processes cool the product before discharge.

The HyL (Hojalata y Lamina) process uses retort reactors. The process is a batch operation and the charge is prereduced, reduced, cooled, and

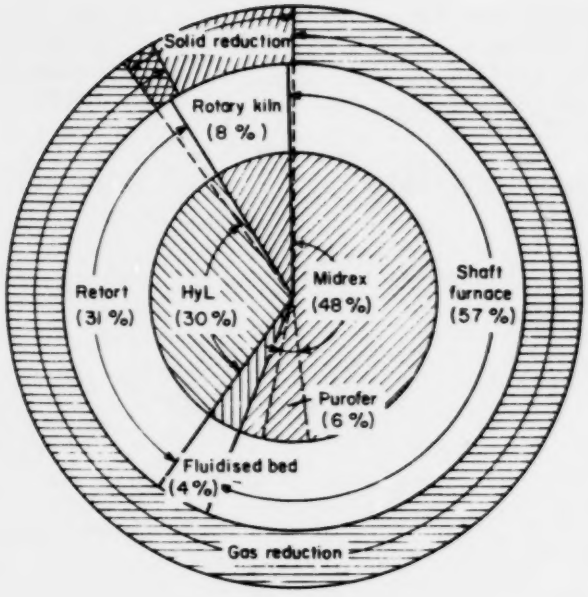

Figure 2. Types of Direct Reduction processes (1)
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TABLE 3. SPONGE IRON PRODUCTION CAPACITY BY PROCESS TYPES (1978)

Gas Reductant (80.2%)	Solid Reductant (19.8%)
Shaft Furnaces (38.7%)	Rotary Kiln (16.0%)
Midrex (27.4%)	SL/RN (7.9%)
Purofer (7.6%)	Japanese (6.7%)
Armco (3.1%)	Krupp (1.4%)
Wiberg (0.6%)	
Retort Furnaces (26.7%)	Retort (2.5%)
HyL (26.7%)	
Fluidized Bed Furnaces (10.7%)	Others (1.3%)
HIB (7.0%)	
FIOR (3.7%)	
Others (4.1%)	

discharged as separate operations.

There are two commercial fluid bed processes, the HIB (high iron briquette - U. S. Steel) process and the FIOR (fluidized iron ore reduction - Esso Research) process.

The main process using solid reductants is the rotary kiln. The rotary kiln systems used on an industrial scale are the SL/RN (Stelco, Lurgi, Republic Steel, National Lead) and Krupp processes. The iron containing feed material is either lump ore or pellets. This differentiates the two processes from the Japanese rotary kiln reactors that use pelletized steelplant dusts from the feedstock; e.g., Kawasaki process, Nippon Steel's Koho process, and Sumitomo Metals SPM and SDR processes.

In March 1978 a rotary kiln facility was started up in Rockwood, TN. The process (Azcon Corporation) utilized pellets as the iron source and coal as both the energy and reductant sources.

Another process that utilizes a rotary kiln is the ACCAR (Allis Chalmers Controlled Atmosphere Reduction) process. Oil and natural gas are the heat and reducing sources.

A few other low production solid reductant systems are in operation; e.g., the Kinglor-Metor and the Hoganas processes. The Kinglor-Metor process is a shaft furnace that uses coke, coke breeze, or lignite as the reductant and external heating as the energy source. Muffle furnaces are used to reduce batch charges of ore and coke breeze in the Hoganas process.

Gas Reductant Systems

More than 80 percent of the world's sponge iron is provided by gas reductant systems. About half of this amount is produced in shaft-type furnaces; about a third is produced in retort furnaces. The remainder is produced in fluid-bed reactors.

The feed material to gas reductant systems can be lump ore, pellets, or ore fines. The shaft furnaces require lump ore, pellets, or briquetted fines. The fluid bed processes require ore fines. The ore feed size requirements are depicted graphically in Figure 3.

The feed material to a direct reduction plant is carefully controlled; not only the feed material particle size distribution but also the feed chemistry. Each plant operation has its own chemical specifications for the material it buys. The specification is influenced by not only the type of direct reduction reactor system but also by the subsequent end use. An illustrative specification is an iron content of at least 65 percent, a gangue content $(SiO_2+Al_2O_3)/Fe$ ratio < 5 percent; and a phosphorous and sulfur content < 0.05 percent and < 0.01 percent, respectively.

The Midrex Process

From published literature it appears that the Midrex process is being

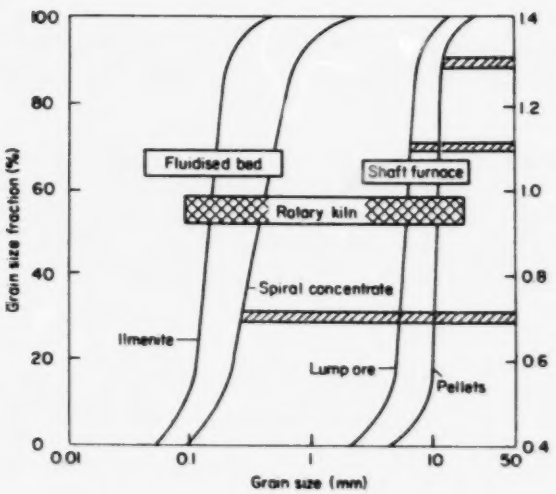

Figure 3. Feed material size distribution (1)
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used at 10 locations. The companies using the process, their location, and production capacities are given in Table 4. About 7 million tonnes per year of sponge iron is produced by this process. Midrex (12) predicts, based on present contracts and agreements, that the production capacity by 1981 will be 17 million tonnes/year.

The largest single gas reductant furnace in the world is now on stream at Contrecoeur, Canada; it is a single reactor with a rated capacity of 600,000 tonnes/year (9). This increases the production capacity of Sidbec-Dosco's two reactors to over 1 million tonnes per year of direct reductant iron.

Detailed process information is available on the two Midrex facilities in the United States (13-16), the Sidbec-Dosco facility in Canada (17-19) and the Dalmine Siderca, Sidor, and Acindar plants in Latin America (19). All of the plants are based on modules that have a 400,000 tonnes/year capacity except the Sidbec-Dosco II facility (17) which has a 400,000 and a 600,000 tonne/year module. Only a brief general description of the process will be presented here. See the noted references for further details.

The Midrex standard flowsheet is presented in Figure 4. The process consists of a reduction shaft furnace and a gas reformer plant. The shaft furnace is 16 feet (4.88 meters) in diameter and is rated at 400,000 tonnes/year. The reactor is divided into a reduction zone and a cooling zone. In the reducing zone iron oxide is reduced as it moves countercurrent to the injected reducing gas. The reactions of interest are the reduction reactions and the formation of iron carbide reaction:

$$2Fe_2O_3 + 3(CO+H_2) \rightarrow 4Fe + 3(CO_2+H_2O)$$

(reduction) (800-1000°C)

$$3Fe + CO + H_2 \rightarrow Fe_3C + H_2O$$

(carburizing)

The product gas exits the furnace near the top. It is cooled, cleaned by a scrubber to remove the particulates, mixed with new natural gas, and passed to a reformer to form more CO and H_2.

The reformer furnace contains long alloy tubes heated externally. The reactions of interest are:

$$CH_4 + CO_2 \rightarrow 2CO + 2H_2$$

(1100-1150°C)

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

The top gas from the reducing furnace is the source of the required oxidants; additional air or steam is not required for the reforming reactions. Some of the top gas which contains about 75 percent CO + H_2 is used as

TABLE 4. MIDREX PROCESS (1,4,12,20)

Operator	Location	Capacity, tonnes/yr
Oregon Steel	Portland, OR	400,000 (1969)*
Georgetown Ferreduction	Georgetown, SC	400,000 (1971)
Hamburger Stahlwerke	Hamburg, West Germany	400,000 (1972)
Sidbec-Dosco I	Contrecoeur, Canada	400,000 (1973)
Sidbec-Dosco II	Contrecoeur, Canada	600,000 (1977)
Dalmine Siderca	Campana, Argentina	330,000 (1976)
Sidor I	Mantazas, Venezuela	400,000 (1977)
Sidor II	Matanzas, Venezuela	1,200,000 (1978) (3-400,000 plants)
Acindar	Villa, Argentina	420,000 (1978)
NISIC	Ahwaz, Iran	1,200,000 (1978) (3-400,000 plants)
Qatar Steel	Doha, Qatar	400,000 (1978)
British Steel	Hunterston, Gr. Britain	800,000 (1978) (2-400,000 plants)
	Total (1978)	6,950,000**

* Start date

** The total capacity is based on published literature figures. However, from private communications with J. Bradley, Midrex Corporation this figure should be 6,065,000 tonnes per year (August 29, 1979).

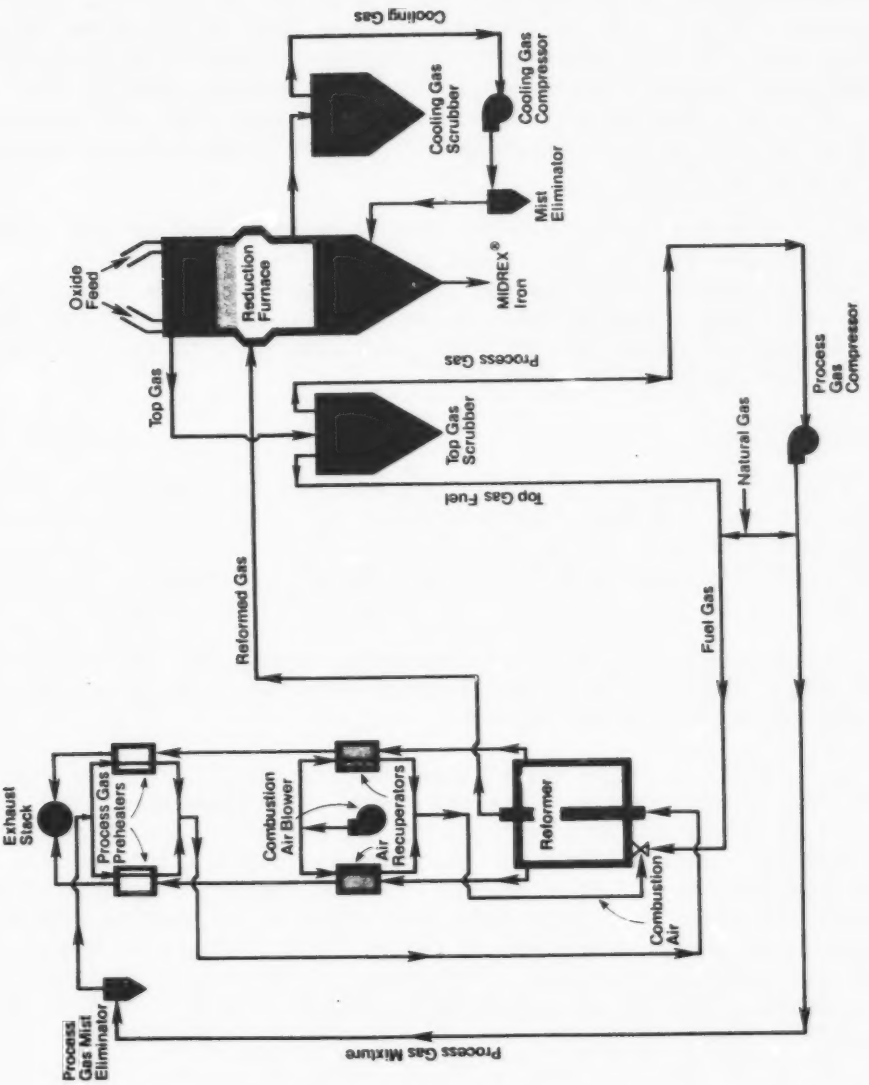

Figure 4. Midrex standard flowsheet (18).
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fuel for firing the reformer chambers.

Hot metallized sponge iron descends into the cooling zone of the furnace. It is cooled by a closed loop of circulating inert or natural gas. The cooled iron product is discharged continuously at about 30-50°C.

The iron product may be further treated to prevent it from reoxidizing during storage. Midrex has developed processes that are used for passivating the product; e.g., a controlled slow reoxidation of the iron surface and a cold briquetting process that reduces the total surface area so that reoxidation is of minor importance. However, in both cases the passivated product must be stored in areas protected from rainwater and/or seawater during transportation.

It is of interest to compare the energy requirements of gas reductant systems. Kalla and Steffen (1) report the results shown in Table 5. The Midrex, Purofer, and Armco processes require about the same energy, with the Midrex requiring slightly less than the other two. The Midrex 600,000 tonne/yr (Sidbec II) plant has reported even lower energy use, 2.5 Gcal/tonne Fe for gas consumption usage (21).

The HyL Process

The Hojalata y Lamina S.A. (HyL) process is currently (end of 1978) being used at nine locations. The companies using the process, their location, and production capacities are given in Table 6. About 7 million tonnes per year of sponge iron is produced by this process. Projections (4) are that capacity will be increased to about 9 million tonnes/yr by 1981.

Detailed process information is available on the HyL facilities in Mexico (22-24). Only a brief general description will be presented here. See the references for further details.

The HyL process operates on a fixed bed principle. The ore remains stationary in a closed retort. The gas phase is changed according to the operation to be performed in the reactor; i.e., drying, preheating, reduction, and cooling. A flow sheet for the process is shown in Figure 5 (7). A process module consists of four reactors. Each reactor is about 17 feet (5.18 meters) in diameter and 49 feet (14.9 meters) in height. Three of the four reactors are always connected in series (with respect to gas flow) while the fourth is loaded or unloaded. The steps in the reduction cycle consist of first reactor - loading and unloading, second reactor - initial reduction, third reactor - final reduction, and fourth reactor - cooling and carburizing.

Each retort is discharged every 9-12 hours. The sequence of treatment occurring in each reactor is: fresh reformed gas is used to cool the reduced product; it then passes on to another retort where final reduction takes place; and gas from this reactor is passed through a third reactor where preheating of the charge and preliminary reduction occurs. Gas from this stage of the operation still contains enough $CO + H_2$ to be used as fuel for firing the reformer combusters. Note that the product gas from the last

TABLE 5. ENERGY REQUIREMENTS FOR THE GAS REDUCTANT SYSTEMS (1)

Process	Reducing Agent H_2	CO	CO_2	H_2O	(CH_4+N_2)	Gas (Gcal/Tonne Fe)	Gross Energy Consumption Electricity (kWh/tonne Fe)	Total Equivalent (Gcal/tonne Fe)
Midrex	53	35	2	5	5	3.1	155	3.2
HyL	75	14	8	-	3	4.6	15	4.6
Pruofer	47	45	2	3	3	3.3	130	3.4
Armco	68	20	2	9	1	3.4	35	3.4
FIOR	75	14	8	-	3	4.0	150	4.1
Blast Furnace (25)								2.8

TABLE 6. HyL PROCESS (1,2,4,22)

Operator	Location	Capacity, tonne/yr
HYL I	Monterrey, Mexico	95,000 (1957)*
HYL II	Monterrey, Mexico	260,000 (1960)
HYL III	Monterrey, Mexico	475,000 (1974)
TAMSA	Vera Cruz, Mexico	280,000 (1967)
HYL I	Puebla, Mexico	315,000 (1969)
HYL II	Puebla, Mexico	625,000 (1977)
USIBA	Bahia, Brazil	250,000 (1974)
SIDOR I	Matanzas, Venezuela	400,000 (1977)
SIDOR III	Matanzas, Venezuela	350,000 (1977)
SIDOR IV	Matanzas, Venezuela	2,000,000 (1978)
NISIC III	Ahwaz, Iran	400,000 (1978)
Krakatau-Ferrosteel	Kota Baja, Indonesia	500,000 (1978)
Tika	Solwezi, Zambia	300,000 (1978)
Iraq	Khor El Zubeir, Iraq	600,000 (1978)
	Total (1978)	6,850,000

* Start date

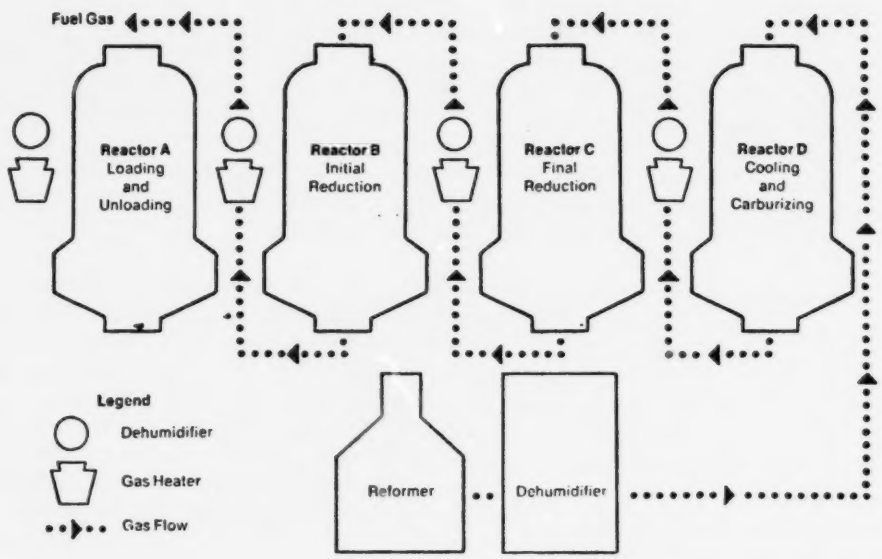

Figure 5. The HyL process (27).
(Reproduced with permission of Iron and Steel Engineer.)

reactor is not recycled for reforming as is the product gas from the Midrex furnace.

The HyL product is normally controlled at about 85 percent metallization and contains up to 2.5 percent C. It is claimed that the product is nonpyrophoric (22) The energy requirements were reported by Kalla (Table 5) to be 4.6 Gcal/tonne Fe. This is somewhat higher than the value reported by Labee (22) for the HyL Puebla II plant; i.e., 3.4 Gcal/tonne product (which is approximately equivalent to 4 Gcal/tonne Fe).

Other Processes

The Midrex and HyL processes accounted for over 88 percent of the metallized iron produced by gas reduction processes in 1978. The other gas reduction processes, their production capacities, and locations are presented in Table 7.

The Purofer (26) and Armco (27) processes are both shaft furnace processes that are similar in principle and design to the Midrex process. Both processes involve the flow of solids countercurrent to the flow of reducing gas. The feeds are similar to the Midrex and the results of metallization essentially the same, 92-94 percent. The differences are that the Armco process does not recycle the reducing gas and the Purofer process discharges its product hot. The hot product is briquetted before release and is therefore nonpyrophoric. Another difference is that the Purofer process can use either oil (gasified) or natural gas as the reductant.

Two other gas reduction processes use fluid-bed reactors; i.e., the HIB (high iron briquette) process (28) and the FIOR (fluidized iron ore reduction) process (29). Both are U.S. developed processes but commercialization has taken place in foreign countries; see Table 7. The FIOR process produces a product that is 88-93 percent metallized whereas the HIB process is designed for the product to be used in ironmaking rather than steelmaking, hence its metallization is much lower; i.e., 70-75 percent Fe. The products from these processes are a fine powder that has been produced at low temperatures and is, therefore, pyrophoric. The product is briquetted to prevent reoxidation during storage.

Solid Reductant Systems

Approximately 20 percent of the world's sponge iron capacity is provided by solid reductant systems (1978). Most of the capacity is in rotary kiln reactors (16%) and a small amount is retorts (2.5%) and vertical shaft furnaces (1.3%). The solid reductant systems, their production capabilities, and their location are presented in Table 8. (There are several discrepancies in the production figures given by references 1, 2, and 4.) In addition to those processes listed in Table 8, a number of rotary kiln furnaces treat steel plant dust, see Table 9.

Approximately 90 percent of the production from solid reductant systems is by rotary kiln processes, 2,170,000 tonnes/yr from virgin ores and 1,725,000 tonnes/yr from mill wastes. According to Miller (4), "There has

TABLE 7. GAS REDUCTANT PROCESSES
EXCLUDING MIDREX AND HYL (1978) (1,2,4,22)

Process	Operator	Location	Capacity, tonnes/yr
Purofer	Thyssen-Purofer	West Germany	150,000 (1970)*
Purofer	COSIGUA	Brazil	350,000 (1977)
Purofer	NISIC	Iran	330,000 (1970)
ARMCO	ARMCO	USA	330,000 (1972)
FIOR	Fior de Venez	Venezuela	400,000 (1976)
HIB	MONORCA	Venezuela	650,000 (1973)
		Total (1978)	2,210,000

*Start date

TABLE 8. SOLID REDUCTANT SYSTEMS (1978) (1,2,4)

Process	Location	Reactor Type	Capacity, tonnes/yr
Hoganas	Sweden	Muffle	170,000
Hoganas	USA	Muffle	70,000
SL/RN	New Zealand	Rotary Kiln	120,000
SL/RN	Brazil	Rotary Kiln	60,000
SL/RN	Canada	Rotary Kiln	360,000
SL/RN	Peru	Rotary Kiln	100,000
Krupp	S. Africa	Rotary Kiln	150,000
Highveld Kiln	S. Africa	Rotary Kiln	1,000,000
Highveld Kiln	S. Africa	Rotary Kiln	300,000
Hockin Kiln	USA	Rotary Kiln	100,000
Kinglor-Metor	Italy	Shaft	40,000
		Total (1978)	2,470,000

TABLE 9. ROTARY KILN PROCESSES FOR TREATING STEEL PLANT WASTES (1,2,4)

Process	Location	Capacity, tonnes/yr
SL/RN	Fukayama, Japan	490,000
Sumitomo	Wakayama, Japan	340,000
	Kashima, Japan	290,000
Kawasaki	Mizushima, Japan	310,000
	Chiba, Japan	85,000
NSC	Hirohata, Japan	210,000
	Total (1978)	1,725,000

been no general acceptance of the rotary kiln processes. Solutions for frequent electrical and mechanical breakdowns and for complex operating difficulties have been neither easy nor consistently successful, and start-up periods have been longer than planned."

It should be noted that the SL/RN plant in Canada (30) has been shut down since May 1976 (4). An additional facility, not listed in Table 8, uses a mixture of coal and oil; i.e., the Allis Chalmers Controlled Atmosphere Reduction (ACCAR) rotary kiln (50,000 tonnes/yr). A second ACCAR kiln is located at Sudbury, Canada (capacity 340,000 tonnes/yr) but the reductant and fuel are a mixture of oil and natural gas. It has been out of operation since October 1976 (4).

According to Miller (4) there appears to be reason for some optimism for rotary kiln processes: "There has been an increasing number of encouraging reports since 1975 from the modified SL/RN unit in New Zealand, the Krupp plant in Benoni, and the Highveld operation in South Africa, and especially from several kiln operations with steelplant waste-material charges in Japan. The sponsors of coal-based processes believe, therefore, that the breakthrough by their designs is very close."

Another recent development also lends optimism to the use of coal based rotary kiln processes; i.e., the Western Titanium, Ltd. coal fired Hockin process (32). This process was developed in Australia and is now being demonstrated by the Azcon Corporation at its Rockwood, TN plant. It is a rotary kiln process that uses coal for both the reductant and the fuel. No other fuel is required.

A comparison of the energy requirements for solid reductant systems is presented in Table 10. To compare these values with gas reductant systems refer to Table 5. The average energy requirement per tonne of iron produced by direct reduction (all processes included) falls within the range 3.8 ± 1.0 Gcal/tonne Fe. It has been reported that the production of pig iron by the blast furnace uses approximately 2.8 Gcal/tonne Fe (1973 figure, Kono (25)). This energy value is for Japanese practice and is, likely, considerably less than United States energy consumption. According to Dailey (33), the best North American blast furnace practice (1972) required 5 Gcal/tonne Fe. Depending on the basis of comparison, one can state that direct reduced iron can be (a) produced at a lower energy input than pig iron (e.g., any direct reduction practice compared to "best" North American blast furnace practice) or (b) produced at essentially the same energy input required for "best" blast furnace produced pig iron (e.g., Japanese blast furnace practice compared to any direct reduction practice). At one time or another all of these claims have been reported in the literature. Often the assumptions used in making the comparisons are not clearly stated and care must be exercised in using the results.

The SL/RN Process

Rotary Kiln processes are similar in principle. Kilns are long cylindrical refractory lined vessels that can be rotated about their longitudinal axis. The vessel is tilted at about a 3 percent slope. Feedstocks

TABLE 10. ENERGY REQUIREMENTS FOR SOLID REDUCTANT SYSTEMS

Process	Total Equivalent Energy Consumption Gcal/tonne Fe	Reference
SL/RN	3.7 - 4.8	1, 34
Krupp	3.8 - 4.8	1, 34
Hockin	3.2	32
Kawasaki	3.5 - 4.2	34
Accar		
Coal/Oil	2.8 - 3.3	35
Oil	3.0 - 3.3	35
Gas	3.5 - 3.8	35
Kinglor-Metor	4.2	5, 36

(usually lump or pelletized ore), fluxes, and coal are fed in the high end of the vessel. The ore is preheated and reduced as it is moved by the vessel's rotation and gravity. The reduced material is discharged continuously from the lower end of the kiln into a cooling or briquetting system.

The rotary kiln processes differ mainly in design of the heating system and in the selection of operating conditions such as type of ore, type of coal, feed rates, gas and solid temperatures, and oxygen potential.

The SL/RN process will be briefly described here as an illustration of rotary kiln processes. Further detailed descriptions are readily available in current literature for all the rotary kiln processes (11,20,28,30,37,38).

A flow diagram (7) is presented in Figure 6. The selection of feed materials is very important. The reactivity of the ores is carefully tested before they are accepted for use in the reactor. The gangue content, base/acid ratio, sulfur, phosphorus, alkaline metals, and heavy metal contenare all specified and tested before an ore is purchased. The physical properties are also important; e.g., strength, size. "Contrary to a misconception that is more widespread than it should be, direct reduction will not work with 'any' ore" (7).

The type of coal is also specified and tested before acceptance for use in a solid reductant kiln. It must have a proper reactivity, a specified low sulfur, phosphorus and volatile content, and a minimum fusion temperature. A coal that does not have a proper fusion temperature can agglomerate and stick to the reactor walls and rather quickly shut down the reactor.

The kiln temperature is controlled by a series of burners along the length of the kiln. Ore and coal are charged into the kiln (up to 100 meters long). Limestone and dolomite may be included if the sulfur content is to be maintained at low levels.

The solid mixture is heated to about 1000°C (this varies depending on ore and fusion temperature of the coal) as it moves along the kiln. The residence time is 3-4 hours and the metallization is from 92-95 percent. The discharged product is cooled and screened, and the iron is magnetically separated from the coal char.

The waste gases are further burned in an afterburner or are scrubbed and the waste gas flared.

Other Solid Reductant Systems

There are a few nonrotary kiln processes; e.g., the Hoganas and Kinglor-Metor (39) processes. The Hoganas process is based on the use of muffle furnaces and the Kinglor-Metor process is an externally heated shaft furnace system. Neither process is considered suitable for large scale development and, therefore, will not be discussed here.

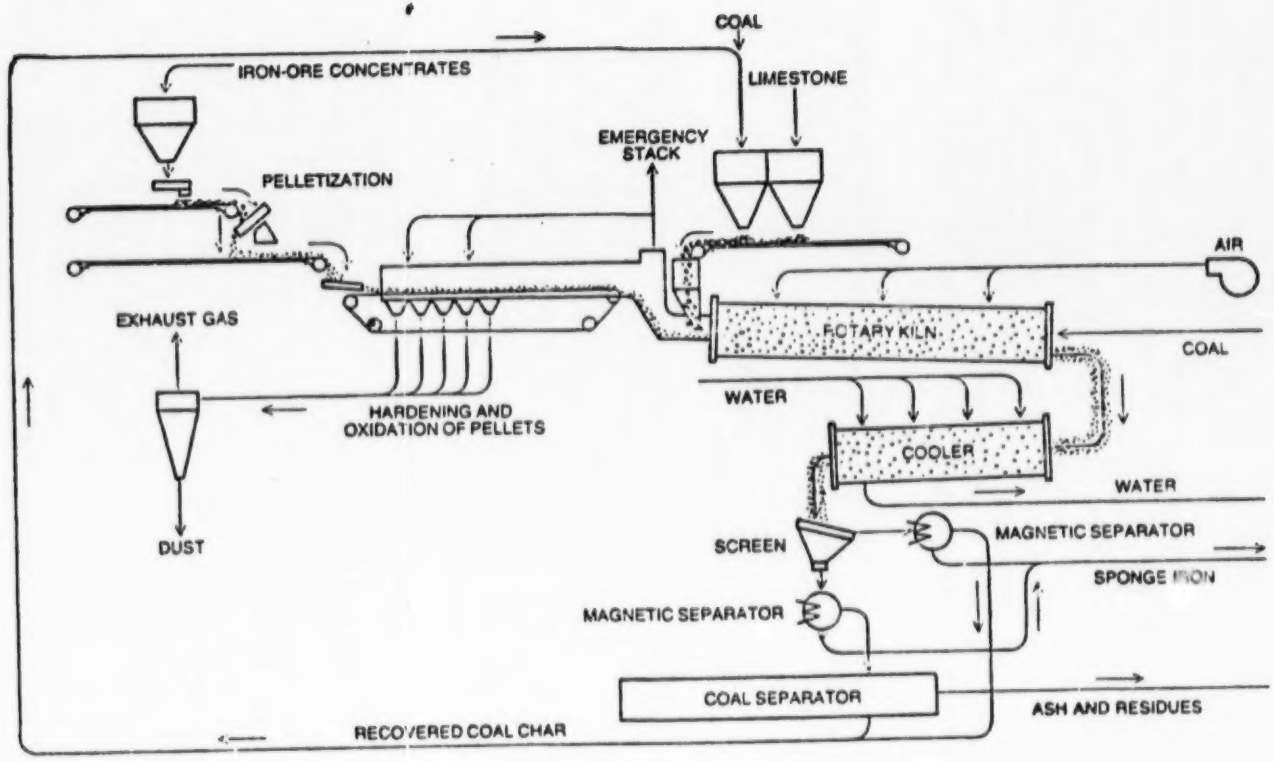

Figure 6. The SL/RN process (7).

Direct Reduction in the United States

The near future prospects for U. S. adoption of direct reduced ironmaking is at this time questionable. The present direct reduced iron capacity in the United States (4) is 1.1 million tonnes per year. This production capacity is projected (4) to increase to 4.32 million tonnes per year by 1985 (Table 2). About 2.4 million tonnes per year of the projected increase is based on natural gas reduction units. The proven reserves in the lower 48 states amount to 200 trillion cubic feet (Tcf). Our current rate of consumption is 19 Tcf per year. Therefore, unless the quantity of proven reserves increases dramatically, a supply of only 10 years exists. Even if an optimistic view is taken that the reserves can be doubled by acquiring gas from Alaska and Mexico and/or by production of synthetic gas from coal, only a 20 year supply at current consumption rates could be possible. Therefore, coal or coal derived products appear to be the only fuel type that can be realistically considered for direct reduction use (40, 41).

Hayes (42) estimates that by 1985 the United States production of coal will be 818±18 million tonnes per year. The reserves of coal are estimated by the Bureau of Mines to be 397 billion tonnes (42). Of the available coal, Hayes estimates that 227 billion tonnes is recoverable. It, therefore, appears from the projected supply and demand estimates that coal will be an energy form available for many years.

Coal-based direct reduction systems have been discussed previously in the section, "Solid Reductant Systems." There are commercial plants presently producing iron. Recent progress in the technology of solid reductant processes, particularly rotary kiln reactors, was reviewed at a recent Office of Technology Assessment (O.T.A.) Seminar on New Techniques in Steelmaking (41). The presentations on the SL/RN (43) and ACCAR (44) rotary kiln processes suggested that the major technical problems experienced in operating rotary kilns have been solved.

The successful demonstration of a new technology is an important step toward the adoption of that technology by industry. But the successful demonstration of new technology does not ensure that it will be adopted even if it is shown to be superior to the old technology (45). Consideration of the factors that impact on the near future adoption of direct reduction technology in the United States is beyond the scope of the present project; e.g., impact of foreign steel imports, availability and price of scrap, expected replacement of old facilities, and need for new capital formation. However, these factors are being considered in a comprehensive Office of Technology Assessment study, "Impact of Technology on the International Competitiveness of the United States Steel Industry" (46). The results of this study will be available in the Fall, 1979. Conclusions of the study and resultant policy decisions may have an important impact on the near future development (or nondevelopment) of direct reduction ironmaking in the United States.

SECTION 3

POTENTIAL POLLUTION PROBLEMS

One of the attractive features of the direct reduction route to iron-making is that the processes can be effectively controlled to prevent major emissions to the environment. The following discussion outlines several potential pollution problems but each of the potential problems can be eliminated by good process design and control.

Gas Reductant Systems

The shaft furnace gas reductant systems produce some particulate material. The origin of the particulate material is feed deterioration brought about by abrasion and reduction reactions.

The gas exiting the shaft furnace contains unreacted CO, H_2, CH_4, reacted products, CO_2, H_2O, and dust particles. This gas is normally treated in wet scrubbers and the cleaned gas is recycled to the gas reforming unit and subsequently back to the reactor furnace. The particulate solids in the scrubber waters are recovered and then briquetted, pelletized, or disposed of in solid waste storage areas.

It is important to note that gas reductant systems operate under conditions that are unfavorable for formation of polynuclear aromatic hydrocarbons (PAH); e.g.,

1. Low order hydrocarbons are used in the reforming process (CH_4) and they are not likely to combine to form the high order PAH's.
2. Reforming is conducted by surface catalyst techniques which do not promote formation of high order molecules.
3. The reduction reactor is operated at temperatures (≈950°C) below which PAH's form.

Even if PAH's are formed in the reduction furnace they probably are effectively removed from the gas streams along with the scrubber sludge. The fate of PAH's in the scrubber water is not known. It is suspected that some of the PAH material will dissolve in the aqueous phase (the low molecular weight compounds) and some will remain with the solids either as condensed particulate organic solids (the high molecular weight compounds) or as adsorbed species on the solids. That fraction of the PAH material that is not removed by scrubbing should not be a problem because the gas stream is either recycled to the reduction furnace or is combusted in a separate chamber.

Even if PAH's are formed and removed by scrubbing, they would most likely not be a problem at those facilities that recycle their solids to the direct reduction furnace and their water to the scrubber system. Some facilities do not recycle the sludge solids but dispose of them in solid waste storage areas. The final fate of any PAH material (if it even exists) in the solid waste is not known.

As is true at all facilities that have ore storage, wind blown dust is a potential pollution problem. The sponge iron product is not a pollution problem because it is normally placed in protective enclosures or covered with canvas to prevent reoxidation by exposure to moisture.

The literature suggests that gas reductant systems can utilize the product from a coal or oil gasification plant (47). If this occurs, the potential pollution problem associated with gasification plants must also be considered (48).

Another associated source of potential pollution needs to be considered; i.e., pelletization. It is estimated (1) that 90-150 million tonnes per year of ore, that has acceptable chemical composition for use in direct reduction, is available. However, about 70 percent of this material is fine-grained. The fine-grained material is useful for fluid-bed applications but the size range necessary for use in the fluid-bed reactors is fairly narrow. Therefore, a significant fraction of the ore will most likely have to be agglomerated before it can be used. Emissions from iron ore mining, beneficiation, and pelletizing have been studied by Midwest Research Institute for the EPA. Potential emission sources are discussed in reference (49).

Note that pelletization of ore fines is not unique to direct reduction feed materials: it is also used extensively for preparation of blast furnace feed material. In fact, only about 3 percent of the pellets produced at present are used in direct reduction processes (2).

Solid Reductant Systems

The gas from a rotary kiln coal reductant system could contain CO, CO_2, H_2, H_2O, SO_x, NO_x, hydrocarbons, trace metals, and particulate matter. Most systems combust natural gas or oil above a coal/ore mixture to maintain the desired temperature. Two systems use coal both as the reductant and as the combustion fuel; i.e., Azcon Corporation's Hoskin process reactors in Australia and Rockwood, TN. The effluent gas phase composition from rotary kiln reactors is very dependent on the coal chemistry and mineralogy. Stringent requirements must be imposed on the coal to limit both the sulfur and trace metal content. The particulate matter from these reactors is usually high in flyash and char. Some systems combust the exit gas in an afterburner chamber to reduce the concentration of CO, H_2, char, and hydrocarbons in the exit streams. The afterburner is normally followed by a wet scrubber device. The collected scrubber product may be dewatered and the solids pelletized or briquetted and recycled to the kiln, but usually they are simply disposed of in solid waste areas.

The product from the kiln is screened and the iron is magnetically

separated from the char and other waste solids. The other waste solids are calcium sulfate (if the feed contains some sulfur, it can be controlled by adding lime to the charge) and a slag-like material from the coal. The larger char material is recovered and recycled to the kiln. The fine char material is disposed of along with the slag and gypsum in solid waste storage areas.

The potential pollution problems are:

1. The survival of PAH's formed in the coal-ore bed. It has been well documented that PAH material is created and/or evolved during pyrolysis and combustion of coal (50-62). Coal fired heating and power generating plants are estimated to contribute over 30 percent of the BaP (Benzo-alpha-pyrene, a member of the Polynuclear Aromatic Hydrocarbon group of chemicals that is known to be carcinogenic) emitted to the United States air environment each year (62), and over 45 percent to the world's air. It is, therefore, reasonable to suspect the rotary kiln processes of being potential Polynuclear Aromatic Hydrocarbon emitters.

The gas phase above the rotary kiln bed is normally oxidizing and will, therefore, be expected to combust the organic material if the retention times are long enough. The entrance region of the kiln appears to be an ideal place for the formation of PAH compounds; i.e., the material is being preheated and volatile constituents are being evolved; soot is also being evolved (in effect the material is smoldering). The PAH compounds evolved into the gas phase will be oxidized if the retention times in the oxidizing zone above the bed are sufficiently long. However, near the feed end of the kiln the retention times will be very short. Also, it appears likely that PAH compounds readily adsorb on fine particulate matter, in particular soot, and that the PAH compounds are protected and survive if the retention times are short.

2. The survival of PAH's from the combustion of oil and coal above the coal/ore mixture. The survival of organic compounds evolved during the combustion of the fuel is expected to be very low. The kiln gas temperature (32) varies from approximately 1200°C at the burner end to 500°C at the gas exit end. An exposure at greater than 900°C for at least 0.3 sec is necessary for destruction of the PAH material. The gas flow rates generally allow an average residence time in the reactor of from 5 to 9 sec. Therefore, the destruction of most combustion formed PAH material is expected to occur during steady state operation. However, emission of PAH compounds during start-up and shut-down periods is expected to be considerable.

As stated earlier, some rotary kiln processes treat the kiln gases in an afterburner and then scrub the gas in wet scrubbers. Therefore, the PAH material that survives the combustion is most likely collected in the scrubber sludge. Its fate in subsequent processing or in solid disposal sites is uncertain at this time.

The Minimum Acute Toxicity Effluent (63,64) value for BaP disposal to land is 0.006 μg/g. This is not a regulation-restricted emission value but indicates minimum concentrations suspected of potential health effects. One

should be aware that this value is considered controversial because the natural background of BaP in soils and sediments is often quoted to be much greater (65-67).

3. Trace element and sulfur oxide emissions from the coal fired reactors. Reactors (only one in U.S. at present) that combust coal above the surface of a coal/ore mixture emit some of the sulfur and most of the trace elements from the rotary kiln. A portion of these elements are removed by the attached control devices.

The sulfur content in the feed coal is specified to be low; i.e., usually less than 0.5 percent. Example calculations using the operating data presented by Cassidy and MacKay (32) for a coal fired rotary kiln (assuming 0.5 percent sulfur in the feed coal and a heating value of 10,000 Btu/lb coal) yield a sulfur emission factor of 0.5 lb sulfur/MM Btu. In terms of sulfur concentration, emission is 0.6 grams per cubic meter. New Source Performance Standards (NSPS) have not been considered for direct reduction reactors. However, if we assume that regulations similar to the proposed NSPS for electric utility steam generating units (68) apply to a coal fired direct reduction reactor, then emission levels above 0.2 lb sulfur/MM Btu would have to be controlled to meet an 85 percent reduction in input sulfur content. About 20 percent of the inlet sulfur will be associated with the slag phase (69) exiting the reactor and should be effectively removed from the gas stream by most particulate control devices. A portion of the sulfur will be "gettered" from the gas stream while still in the reactor by lime in the ore bed. The fraction extracted by this mechanism cannot be estimated because the reaction is dependent on such kinetic factors as efficient gas/solid contact and residence time. It is anticipated, however, that sulfur oxide emissions can be controlled without special add-on sulfur removal equipment.

Sulfur content in the coal used as a reductant in the coal/ore bed has been shown to be effectively controlled by the addition of lime or dolomite to the charge mixture (32). Gypsum is formed and can be separated from the sponge iron and disposed of in a solid landfill site.

The partitioning behavior of trace elements during coal combustion has been studied (59). The fate of trace elements falls into three general classes: those normally partitioned to the slag phase are Al, Ba, Ca, Ce, Co, Eu, Fe, Hf, K, La, Mg, Mn, Rb, Sc, Si, Sm, Sr, Ta, Th, and Ti; those normally partitioned to the fly ash are As, Cd, Cu, Ga, Pb, Sb, Se, and Zn; and those normally remaining in the gas phase are Hg, Cl, and Br. As and Cd are usually more concentrated in the fly ash particle sizes less than 10 micrometers, so concentration occurs in the size fractions that are least effectively removed by control devices. The concentration of trace elements varies in coals and the release of trace elements during combustion varies greatly (60,61). It is certain, however, that great care should be exercised in designing a control system to include good removal of fly ash particles which, most likely, will contain toxic material. National Emission Standards for Hazardous Air Pollutants (NESHAP) are being considered for As, Cd, and Pb (59). Proposed standards have been generated for Be (63).

For example, if one assumes that the concentrations of trace metals given by Thompson and Harrison (59) are representative of coal fuels, and that values for combustion coal feed rates given by Cassidy and MacKay (32) are appropriate, then uncontrolled emissions of As, Cd, Pb, and Be can be calculated.

The concentrations of trace metals in low sulfur coals are:

As	9.3 - 13 ppm
Cd	0.1 - 2.4 ppm
Pb	8.3 - 12 ppm
Be	1.2 - 2.8 ppm

The process feed rates are:

Combustion coal	0.70 tonnes/hr
Air (At Standard Conditions $0^{o}C$, 1 Atm.)	4980 m^3/hr

The calculated trace metal uncontrolled emission values are:

	$\mu g/m^3$
As	1085 - 1517
Cd	12 - 280
Pb	968 - 1400
Be	140 - 326

Control devices will decrease these concentration levels, and dispersion dilution will further decrease the concentration of trace elements emitted to the environment. The NESHAP proposed standard for Be is 0.01 $\mu g/m^3$ as the outplant concentration maximum; therefore, the effect of the control device and dispersion dilution must be to decrease the Be concentration at least 14,000 times.

Recommendations

The gas reductant systems appear to be environmentally clean processes, particularly those that recycle the reductant gas. It is recommended that samples of scrubber effluents be collected and characterized at least through the E.P.A. Source Assessment Sampling System (S.A.S.S.) Level 1 analytical scheme.

The rotary kiln solid reductant systems are of particular interest because of the large U.S. coal reserves. All systems that involve coal and oil combustion have been shown to be potential PAH, sulfur oxide, and trace

metal emitters. It is recommended that an initial sampling be made to ascertain the uncontrolled and controlled emission rates for PAH, SO_x, and trace metals. As an initial effort, a preliminary sampling program should be performed to provide mass balances on these effluents from the rotary kiln and scrubber system.

The only coal fired rotary kiln process in the United States is the Azcon reactor at Rockwood, TN. At present it has neither an afterburner nor scrubber. Sampling of this system for kiln emissions would be desirable.

SECTION 4

STEELMAKING USING METALLIZED PRODUCT

Direct Reduction - Electric Arc Furnace (DR-EAF) Steelmaking

The major use of sponge iron produced by direct reduction processes is as a source of iron in electric arc steelmaking furnaces. Two mini mills (14,16) in the U.S., Georgetown Steel and Oregon Steel, use a substantial fraction of sponge iron in their charge. Both use a charge of sponge iron and scrap, about 50 percent of each.

If the optimistic projections hold -- that 10 percent (100 million tonnes) of the world's iron will be sponge iron (7) by 1985, and that 30 percent (300 million tonnes) of the world's steel will be produced by the electric arc steelmaking process (70) -- significant further growth in the DR-EAF process systems can be anticipated.

The literature quotes a number of advantages for the DR-EAF combination process. Several quoted advantages are presented below:

1. A variety of excellent processes have been developed and proved in commercial operation. These are based upon the moving-bed shaft furnace, the fixed shaft furnace, fluidized beds and the rotary kiln. All represent good technology for tonnages of 900 to 1800 tonne/day. Additional plants can be added as needed, and they can be used with no initial overcapacity as would occur for a modern blast furnace-coke plant-BOF complex (5).

2. For socio-economic reasons, developing nations desire domestic steel industries; limited initial tonnages are the guideline and direct reduction provides moderate scale production at moderate capital investment. Moreover, many of these nations having reserves of high-grade iron ore are deficient in metallurgical coals, but have abundant supplies of natural gas and petroleum. These latter forms of reductant and energy can be used in only limited quantities in blast furnaces but are ideal for many direct reduction processes (5).

3. In developed nations, opportunities occur for mini- and midi-steel mills with direct reduction product supplementing local scrap. These applications will be hampered in the future by high costs and shortages of natural gas or petroleum from which reducing gases can be produced, but processes for economically gasifying coals will

doubtlessly be a favorable future factor (5).

4. The gross consumption of energy per ton of liquid steel is comparable for the method of combining direct reduction and the electric furnace with the blast furnace and the basic oxygen furnace (7).

5. The time required for commissioning a DR-EAF steel plant is about two to three years compared to five to seven years for an integrated steelworks (9).

6. Miller summarized a report by the World Bank comparing DR-EAF to the blast furnace-basic oxygen furnace (BF-BOF):

   a. The quality of common steels produced by DR-EAF and BF-BOF practices was approximately equal;

   b. The estimated capital costs of facilities for pelletizing, iron-making, steelmaking, and continuous slab casting of 3-4 million tonnes/year at Matanzas favor a DR-EAF plant by nearly 40 percent over a comparable BF-BOF installation;

   c. The production cost, excluding fixed charges and income taxes, for a tonne of carbon steel slabs is approximately 20% lower when produced by a DR-EAF operation than when made by the BF-BOF route;

   d. The average rate of return on investment is from 2.5 to 3 times as great for the DR-EAF as for the BF-BOF (4).

7. Korf extols other attributes of DR-EAF systems with conventional BF-BOF steelmaking. Steel production at an EAF plant becomes independent of scrap, a raw material that is volatile in pricing, quality and supply (21).

8. A number of qualities are quoted for the use of sponge iron (versus scrap) as a feed material to electric arc furnaces (71):

   a. chemical composition is known exactly

   b. chemical composition is uniform

   c. contains no undesirable impurities

   d. permits dilution with low cost (more available) scrap

   e. easy to transport and handle

   f. permits automatic continuous charging

   g. increases furnace productivity

   h. less noise during melt down

i. more predictable price structure.

9. Air pollution problems are minimized in a closed cycle gas direct reduction plant because all gases are cleaned and recycled. Effective control of electric arc furnace steelmaking is possible but care must be exercised to assure a nonpolluting operation.

The major disadvantage normally quoted for the direct reduction processes is that they are limited to small production units, whereas blast furnaces are high production units. This argument has been disputed by Dancy (72) and others: "To put the size of this (Midrex) direct reduction plant into perspective in relation to modern blast furnaces, it will produce about 8.0 tonnes/day/m^3 of working volume (bustle to stockline) as compared with only 2.4 tonnes/day/m^3 of a modern 5000 m^3 blast furnace. Furthermore, its production of over 1800 tonnes/day is only a little less than that of the 'average' blast furnace in Japan as recently as 1967 and about the same as that of the 'average' blast furnace in the USA as recently as 1975."

A second disadvantage for direct reduction processes is that they cannot treat a wide variety of ore types, as can the blast furnace. However, direct reduction processes should not be thought of as a means of eliminating conventional iron and steelmaking processes, but a supplement for special applications.

Other Uses of Metallized Product

The major use of metallized product is as a feed material to the electric arc steelmaking furnace, as noted in the previous section. Other uses have been proposed and tested on, at least, a pilot plant scale. These suggested uses are:

a. To increase production and decrease coke requirements in a blast furnace. Miller (4) notes that the literature (73) shows that blast furnace productivity is increased and coke rate decreased by 5-6 percent for each 10 percent increase in furnace burden metallization.

b. To serve as a coolant source in the BOF process for temperature control.

c. To replace the use of scrap in EAF steelmaking processes, in cast iron foundry electric furnaces (73) and cupolas (74,75), and in the BOF process.

Miller (4) proposes that every integrated steelworks should have a direct reduction capability. Its product could be used in one of the ways listed above. Its utility would be to supply prereduced iron wherever it was required. Its source of feedstock would be steelplant fines, dusts from pollution control devices, and supplemental ore. Its reductant would be coke oven gas, blast furnace gas, gasified coal gas or, if a rotary kiln process, coke, coal, or coke breeze.

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